

# New Physics Search with Precision Experiments: Theory Input

A. Aleksejevs and S. Wu

*Grenfell Campus of Memorial University, Corner Brook, Canada*

S. Barkanova

*Acadia University, Wolfville, Canada*

V. Zykunov

*Belarussian State University of Transport, Gomel, Belarus*

The best way to search for new physics is by using a diverse set of probes - not just experiments at the energy and the cosmic frontiers, but also the low-energy measurements relying on high precision and high luminosity. One example of such ultra-precision experiments is the MOLLER experiment planned at JLab, which will measure the parity-violating electron-electron scattering asymmetry and allow a determination of the weak mixing angle with a factor of five improvement in precision over its predecessor, E-158. At this precision, any inconsistency with the Standard Model should signal new physics. The paper will explore how new physics particles enter at the next-to-leading order (one-loop) level. For MOLLER we analyze the effects of dark  $Z'$ -boson on the total calculated asymmetry, and show how this new physics interaction carriers may influence the analysis of the future experimental results.

## I. PRECISION PARITY VIOLATING PHYSICS

The fact of existence of the Dark Matter [1] is one of the most striking evidences that the Standard Model (SM) is incomplete. The further investigation into possible extensions of SM with new physics particles became one of the main goal of both theoretical and experimental particle physics. Searches for physics beyond SM can be summarized into three major directions: energy, cosmic and precision frontiers. The energy frontier is concentrated on the direct production of the new physics particles, which might be accessible at high-energy colliders. In case of the cosmic frontier, direct searches for new physics are coming from underground experiments, ground and space telescopes. The precision frontier is driven by the indirect searches, where new physics particles could impact various observables in SM and hence cause small deviations from original SM predictions. This can be studied by using very precise measurements with intense particle beams. In this paper, we address one of the specific processes used at precision frontier, namely a test of SM using the parity-violating Møller ( $e+e \rightarrow e+e$ ) scattering. The most recent parity-violating Møller scattering experiment, E-158 [2], measured parity-violating right-left asymmetry defined as

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}, \quad (1)$$

and reported the value of  $A_{PV} = (-131 \pm 14 \pm 10) \cdot 10^{-9}$ , which is resulted in the effective weak mixing angle of  $\sin^2 \theta_W^{eff}(Q^2 = 0.026 \text{ GeV}^2) = 0.2397 \pm 0.0010 \pm 0.0008$ . The reported result is found to be consistent with the SM predictions (in the  $\overline{MS}$  scheme):  $\sin^2 \theta_W^{MS}(Q^2 = 0.026 \text{ GeV}^2) = 0.2381 \pm 0.0006$  [3, 5]. In order to put more stringent bounds on the parity violating tests of SM, the MOLLER experiment planned at the

Thomas Jefferson National Accelerator Facility (Jefferson Lab for short, or JLab) [4], will measure  $A_{PV}(Q^2 = 0.0056 \text{ GeV}^2)$  at the level of the  $\delta(A_{PV}) = 0.75$  ppb, which translates to the factor of five improvement in precision for the measurement of the effective mixing angle compared to the E-158 experiment. At this level of precision, the new physics signal may be experimentally detectable, so it is essential to study the potential impact of the new-physics degrees of freedom on the parity-violating cross section asymmetry in the Møller scattering.

## II. DARK PHOTON AND Z BOSONS

In our analysis we choose the simplest extension of SM by the additional  $U(1)'$  symmetry proposed in [6].

Here, the mixing of  $B_\mu(U(1)_Y)$  and  $A'_\mu(U(1)')$  fields is expressed through the kinetic mixing Lagrangian (see Fig.1):

$$\mathcal{L}_{kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B_{\mu\nu}A'^{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}, \quad (2)$$

where  $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ ,  $B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$  and  $\epsilon$  is the  $(B_\mu - A'_\mu)$  mixing parameter. If we assume the simplest scenario for the Higgs sector, which is the SM Higgs doublet plus the Higgs singlet (used for breaking the  $U(1)'$  symmetry and giving mass to  $A'_\mu$ ), a Lagrangian describing interaction between the SM fermions and the dark vector boson  $A'_\mu$ , photon  $V_\mu$  and weak  $Z_\mu$  fields has the following form:

$$\begin{aligned} \mathcal{L}_{int} = & -eQ_f \bar{f} \gamma_\mu f \cdot (V^\mu + \epsilon A'^\mu) - \\ & \frac{e}{\sin\theta_W \cos\theta_W} \bar{f} (c_V^f \gamma_\mu + c_A^f \gamma_\mu \gamma_5) f \cdot Z^\mu. \end{aligned} \quad (3)$$

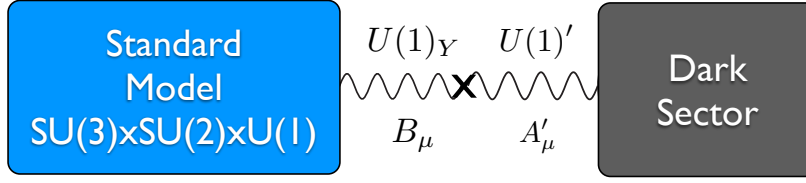


Figure 1: Diagrammatic representation of the interaction between Dark Matter and SM particles through the kinetic mixing between  $U(1)_Y$  and  $U(1)'$ .

Here,  $Q_f$  is the charge of the fermion in units of  $e$ . Vector and axial-vector coupling strengths are defined as follows:

$$\begin{aligned} c_V^f &= \frac{1}{2}T_{3f} - Q_f \sin^2 \theta_W \\ c_A^f &= -\frac{1}{2}T_{3f}, \end{aligned} \quad (4)$$

with  $T_{3f}$  defined as fermion's third component of the weak isospin. The Lagrangian in Eq.3 has only vector-type coupling of dark  $A'_\mu$  to fermions, which is coming from the non-zero kinetic mixing of  $V_\mu$  and  $A'_\mu$  fields. At the leading order, the kinetic mixing term between  $Z_\mu$  and  $A'_\mu$  fields cancels out with their mass mixing term, so as a result  $A'_\mu$  does not have the axial-vector type of coupling to fermions in Eq.3. Hence,  $A'_\mu$  is called a dark photon  $V'_\mu$  ( $A'_\mu \equiv V'_\mu$ ), which resembles a massive photon with the coupling weighted by the mixing parameter  $\epsilon$ :

$$\Gamma_{\mu}^{\bar{f}-V'-f} = -ie\epsilon Q_f \gamma_\mu. \quad (5)$$

A possible extension with non-vanishing mixing between dark  $A'_\mu$  and weak  $Z_\mu$  was explored in [7] with an additional mass mixing term described by the mixing parameter  $\epsilon_{Z'} = \frac{m_{Z'}}{m_Z} \delta$ . Here,  $m_{Z'}$  is the mass of the dark  $Z'_\mu$  boson and  $\delta$  is an arbitrary model-dependent parameter. In this scenario, the interaction Lagrangian is given by

$$\mathcal{L}_{int} = -eQ_f \bar{f} \gamma_\mu f \cdot (V^\mu + \epsilon A'_\mu) -$$

$$\frac{e}{\sin \theta_W \cos \theta_W} \bar{f} (c_V^f \gamma_\mu + c_A^f \gamma_\mu \gamma_5) f \cdot (Z^\mu + \epsilon_{Z'} A'_\mu), \quad (6)$$

and, as we can see from above, the dark  $A'_\mu$  couples to fermions through both vector and axial-vector interactions, which is similar to the weak  $Z_\mu$  coupling. Hence, that type of the dark  $A'_\mu$  in [7] is called the dark  $Z'_\mu$  boson ( $A'_\mu \equiv Z'_\mu$ ). As a result, the coupling  $\bar{f} - Z'_\mu - f$  is written in the following form:

$$\Gamma_{\mu}^{\bar{f}-Z'-f} = -ie \left( S'_V \gamma_\mu + S'_A \gamma_\mu \gamma_5 \right),$$

$$\begin{aligned} S'_V &= \epsilon Q_f + \frac{\epsilon_{Z'} c_V^f}{\sin \theta_W \cos \theta_W}, \\ S'_A &= \frac{\epsilon_{Z'} c_A^f}{\sin \theta_W \cos \theta_W}. \end{aligned} \quad (7)$$

In the case when  $\epsilon_{Z'}$  goes to zero, the dark  $Z'_\mu$  becomes the dark photon  $V'_\mu$ . The coupling in Eq.7 is parity-violating by its nature. In our analysis we use left/right handed (chiral) notation which reflects the nature of the parity-violating interaction by the simple condition of  $g_L \neq g_R$ . Accordingly, in the chiral basis,

$$\Gamma_{\mu}^{\bar{f}-Z'-f} = -ie(S'_L g_L \gamma_\mu \omega_- + S'_R g_R \gamma_\mu \omega_+), \quad (8)$$

where  $\omega_{\pm} = \frac{1 \pm \gamma_5}{2}$  are chirality projectors, and  $g_{\{R,L\}} = c_V^f \pm c_A^f$  are the usual SM right- and left-handed coupling strengths. The scaling parameters  $S'_{\{L,R\}}$  can now be expressed through mixing parameters as:

$$\begin{aligned} S'_L &= \frac{1}{g_L} \left( \epsilon Q_f + \delta \frac{m_{Z'}}{m_Z} \frac{g_L}{\sin \theta_W \cos \theta_W} \right) \\ S'_R &= \frac{1}{g_R} \left( \epsilon Q_f + \delta \frac{m_{Z'}}{m_Z} \frac{g_R}{\sin \theta_W \cos \theta_W} \right), \end{aligned} \quad (9)$$

and the condition for the dark  $Z'_\mu$  becoming the dark photon  $V'_\mu$  is given by  $S'_R g_R = S'_L g_L$ , which is satisfied if either  $\delta \rightarrow 0$  or  $m_{Z'} \ll m_Z$ . Also, if  $S'_R = S'_L = S'$ , dark  $Z'_\mu$  boson becomes the “usual” SM weak  $Z_\mu$  boson with modified mass and scaled coupling by  $\epsilon_{Z'} = \frac{m_{Z'}}{m_Z} \delta$ . The condition  $S'_R = S'_L = S'$  is satisfied if  $\epsilon \rightarrow 0$ .

In this work, we have evaluated the parity-violating asymmetry up to one-loop level with the dark photon or dark  $Z'_\mu$  appearing at the tree level and in the box, vertex, and self-energy diagrams. Representative diagrams for one loop are shown in Fig.2. The diagrams shown in Fig.2 do not contain the Higgs boson because we do not include the coupling of dark vector  $A'_\mu$  to the Higgs field, assuming that the diagrams with the Higgs boson would give a small contribution to the asymmetry. However, for the sake of completeness, we plan to include this interaction in our next work. Using on-shell renormalization scheme for SM and NP fields we have calculated PV asymmetry up to one loop level and included soft-photon bremsstrahlung when treating infrared divergences. For the SM parameters we used last-year PDG values. For the cut on energy of the soft-photons, we choose  $\Delta E = 0.05 E_{cms}$  with  $E_{cms} = 0.106$  GeV.

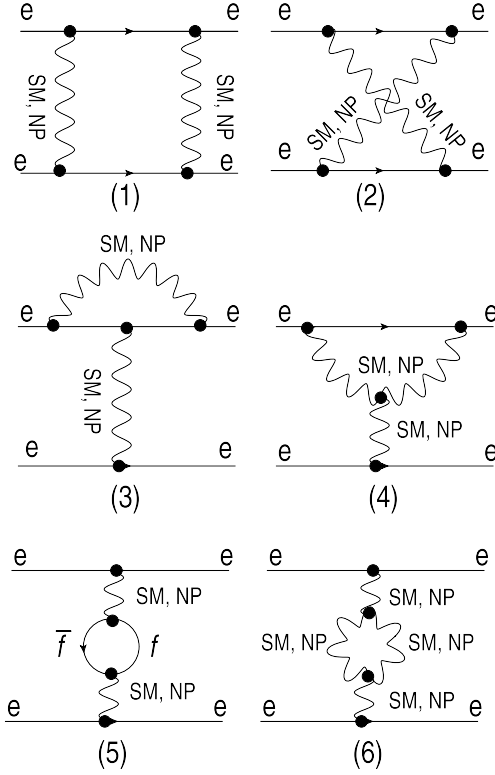


Figure 2: Representative one-loop diagrams for the Møller process with the new-physics (labeled as NP) vector boson in the loops. The label SM stands for the Standard Model vector bosons. In the actual calculations, the diagrams with vertex corrections to the lower electron current and the diagrams for the u-channel are taken into account as well. We also include the gauge fixing terms in the diagrams with  $W^\pm$  in the vertex and self-energy graphs (not shown here).

### III. RESULTS AND CONCLUSION

Our calculation strategy basically consist of the following steps. First, we evaluate the PV asymmetry including one-loop diagrams for the SM particles. This will determine the SM central value. Then we proceed with calculations of the PV asymmetry with the new-physics particles included up to one-loop and construct exclusion plots for 1%, 2% and 3% deviations from the SM central value. Since the MOLLER experiment is mostly sensitive to the parity-violating interaction, which is enhanced through the interference term  $\sim 2\text{Re}[M_\gamma M_Z]$  in the numerator of Eq.1, we concentrate our attention on the analysis of dark  $Z'_\mu$ . The exclusion plots for MOLLER for the case of new physics represented by dark  $Z'_\mu$  are shown in Fig.3.

In the case if the MOLLER experiment does not detect any significant deviations from the SM predictions, then this measurement will exclude everything that is above the corresponding 1%, 2% or 3% lines. Essentially, if MOLLER does not see the dark  $Z'_\mu$ , it will exclude the entire region which would explain the  $g-2$  anomaly with

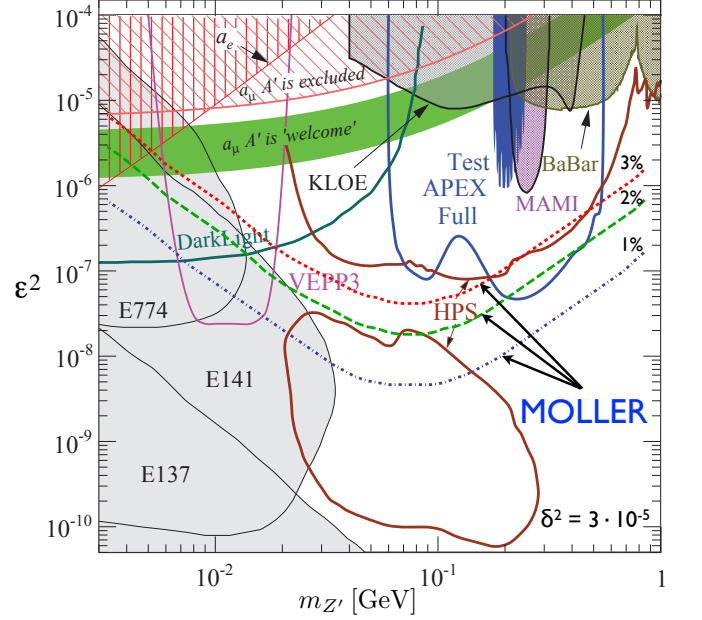


Figure 3: Exclusion plots for the dark  $Z'_\mu$  for the MOLLER experiment with calculations including one-loop in the on-shell renormalization scheme, shown against exclusion plot from [8]. We use  $\delta^2 = 3 \cdot 10^{-5}$ . The blue dot-dashed, green dashed and red dotted graphs correspond to 1%, 2% and 3% the PV asymmetry deviations from the SM prediction, respectively.

the light  $Z'_\mu$  dark boson. A larger value of the  $\delta$  mixing parameter would increase the measurement sensitivity to  $Z'_\mu$  and push the exclusion lines down. Clearly, as one can see from on Fig.3, the MOLLER experiment is very competitive with the DarkLight [9], APEX [10], MAMI [11], KLOE [12] and HPS [13].

Fig.4 shows the exclusion regions for the fixed masses of  $Z'_\mu$  in the space of  $\epsilon$  and  $\delta$  mixing parameters. In the region of the small  $Z'_\mu$  mass (left plot on Fig.4), the overall sensitivity to the variation of  $\epsilon$  and  $\delta$  is quite high but decreases significantly in the region of the higher mass of  $Z'_\mu$  (middle plot of Fig.4). That is mostly related to the suppression coming from the dark  $Z'_\mu$  propagator. If we assume the scenario of the heavy  $Z'_\mu$ , we observe that the sensitivity to  $\epsilon$  and  $\delta$  is enhanced at the leading order by the term  $\sim \frac{\delta}{m_Z^2}$  and loop contribution from  $Z'_\mu$ . A detailed analysis of the one-loop contributions of the dark vector to the PV asymmetry will be addressed in our next work. In the limit when  $\delta \rightarrow 0$  (the dark photon), the sensitivity is weak for all masses of  $Z'_\mu$ . Thus, it is important to have a non-zero (although possibly small) mixing parameter  $\delta$  when it comes to the low-momentum transfer PV experiments such as MOLLER. In the case of  $\epsilon \rightarrow 0$  (the “usual”  $Z_\mu$  boson with the modified mass and scaled coupling), we also observe the reduced sensitivity for the lower masses of  $Z'_\mu$ , so  $\epsilon$  should be non-zero

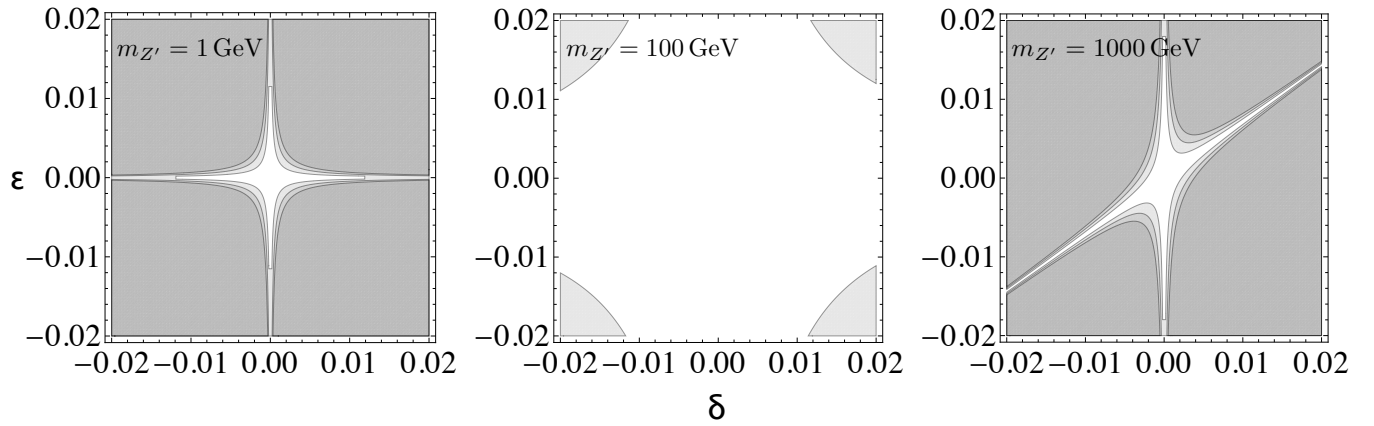


Figure 4: Sensitivity of the MOLLER experiment to the mixing parameters  $\epsilon$  and  $\delta$  for the cases of  $m_{Z'} = 1, 100$  and  $1000$  GeV.

in order to satisfy the constrain  $|\delta| < 1$  (see [7]). For the higher mass of  $Z'_\mu$  (right plot of Fig.4) and the limit when  $\epsilon \rightarrow 0$ , if no significant discrepancy between the measurement and the SM prediction is found, we will be able to say that  $\delta^2 \lesssim 5 \cdot 10^{-6}$ . As we can see, for the low-energy frontier, the probability of finding physics beyond the SM is primarily determined by the level of experimental precision. Therefore advancing that type of experiments in the precision domain could actually open a link to our understanding of the nature of Dark Matter.

#### IV. ACKNOWLEDGMENTS

This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

We are grateful to W. Marciano and J. Erler for the useful discussions and encouragement during the MITP workshop on “Low-energy precision physics” in Mainz in 2013. Also, many thanks to our undergraduate student research assistants M. Bluteau, C. Griebler and J. Strickland for testing the first versions of the code in the summer of 2013. AA and SB thank JLab Theory Group for hospitality during their stay in 2014.

- 
- [1] F. Zwicky, *Helv. Phys. Acta* 6:110–27 (1933).
  - [2] P. L. Anthony et al., (SLAC E-158 Collaboration), *Phys. Rev. Lett.* 95 081601 (2005).
  - [3] A. Czarnecki and W. J. Marciano, *Phys. Rev. D* 53, 1066 (1996).
  - [4] J. Benesch et al., "The MOLLER Experiment" at <http://hallaweb.jlab.org/12GeV/Moller/>, (2014).
  - [5] S. Eidelman et al., (Particle Data Group), *Phys. Lett. B* 592, 1 (2004).
  - [6] B. Holdom, *Phys. Lett. B* 166, 196 (1986).
  - [7] H. Davoudiasl, H. Lee, W. Marciano, arXiv:1203.2947v2, *Phys. Rev. D* 85, 115019 (2012).
  - [8] R. McKeown, arXiv:1109.4855v2 (2011).
  - [9] J. Balweski et al., “Dark Light Proposal” at <http://dmtpc.mit.edu/DarkLight/>, (2012).
  - [10] S. Abrahmian et al., *Phys. Rev. Lett.* 107, 191804 (2011).
  - [11] H. Merkel et al, arXiv:1101.4091v2, (2011).
  - [12] P. Franzini, M. Moulson, *Ann.Rev.Nucl.Part.Sci.*56:207-251 (2006).
  - [13] A. Grillo et al., “HPS: Heavy Photon Search Proposal” at [https://www.jlab.org/exp\\_prog/proposals/11/PR12-11-006.pdf](https://www.jlab.org/exp_prog/proposals/11/PR12-11-006.pdf), (2010).